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# Stress-Strain States Differences in Specimens during Triaxial Compression and Direct Shear Tests

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**Abstract**

This article compares the soil strength parameters obtained from data of triaxial compression and direct shear tests, both with dense samples of fine sand. Direct shear device and triaxial device have significant differences in stress – strain state, which is developed in the specimen during test. In order to evaluate the stress-strain state, the direct shear and triaxial tests were simulated with finite element program PLAXIS 3D.


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*Keywords:* direct shear, triaxial compression, shear strength parameters, sand, stress-strain state.

## 1. Introduction

When the shear stress becomes equal to the peak shear strength along specified plane, the soil will fail. In general, for soil stress states at failure are more often subscribed by the Mohr-Coulomb failure criterion with two shear strength parameters: $\varphi$ – angle of internal friction and $c$ – cohesion. Generally, the direct shear and triaxial devices are used to determine shear strength parameters of soil in laboratory [1].

In triaxial device cell the specimen is enforced by principal stresses. Vertical stress is the major principal stress $\sigma_1$. In a traditional triaxial test confining pressures $\sigma_2 = \sigma_3$ are kept a constant, while the major principal stress $\sigma_1$ is

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increased incrementally until the sample fails. It is assumed that end effect on results will be eliminated when the height of specimen is twice its diameter [2,3].

In the direct shear test the stresses affecting the failure plane are determined directly by applying a normal and shear forces to the sample. The device consists of two rings or rectangular boxes between which shearing plane is formed. Vertical force provides the normal stresses, and the horizontal force causes shear stresses.

These two devices have apparent differences in the stress condition that is developed in the specimen during the test. The main differences are failure plane and principal stress. In direct shear device the failure plane has pre-assigned location, whereas in triaxial device the failure plane is uncertain. In direct shear device the normal and shear stresses on failure plane are calculated directly from acting forces. In the triaxial device the intermediate and minor principal stresses are equal and are normally specified constant, the major principal stress $\sigma_1$ is increased incrementally until the sample fails. Whereas in direct shear device values of intermediate and minor principal stresses are not known.

In order to analyze and evaluate the stress-strain state, the direct shear and triaxial tests were carried out in laboratory and imitated using software [4,5].

## 2. Laboratory tests for soil shear strength determination

Direct shear and triaxial tests were carried out with samples of sandy soil, which according to reference [6], soil is fine sand (FSa). Samples with 6% water content were prepared by compacting them. Samples mass density was $\rho$ = 1,871 g/cm$^3$ and void ratio of $e$ = 0,52. Sand particles has angular shape. For direct shear tests samples 7,14 cm in diameter, 3,41 cm in height were used. The tests were carried out under the normal stress 50, 100, 150, 200 kPa, constant axial strain rate 0,5 mm/min. The samples under the same normal pressure have been sheared at least three times. The test is finished when horizontal displacement of the ring reaches 5 mm. The sample is loaded via hinge by chosen vertical load applying the lever mechanism. Such loading transmitting to sample ensures the constant vertical load on the top of sample, i.e. developing constant normal stress per whole loading history. The normal load is measured at the bottom of the sample during test [7]. The sample is sheared by a constant velocity by moving lower part of the ring. Thus, the shearing velocity is controlled and lateral force is permanently measured.

Triaxial tests were carried out with soil samples, the height/diameter ratio of which was 2. The diameter of samples was $D$ = 5 cm, and height was $H$ = 10 cm. The tests were carried out under the constant cell pressure 50, 100, 200 kPa and the constant axial strain rate 0,1 mm/min. The samples under the same cell pressure have been sheared at least three times. The pore pressure had no influence on test results, tests were carried out in drained condition.

Typical curves of shear stress versus shear displacements for dense sand specimens in direct shear test (Fig. 1) are similar to curves obtained relating deviator stress versus axial strain in drained triaxial compression tests (Fig. 2). The shear stress increased with shear displacement to maximum value $\tau_f$ (peak value) and then decreased to a value $\tau_r$ (residual value).

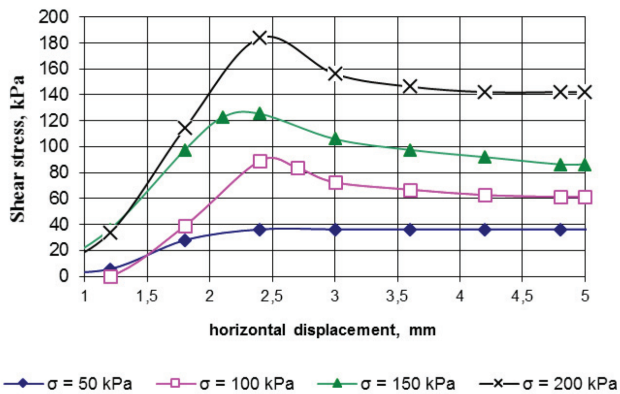


Fig. 1. Shear strength characteristics of sand in direct shear tests.

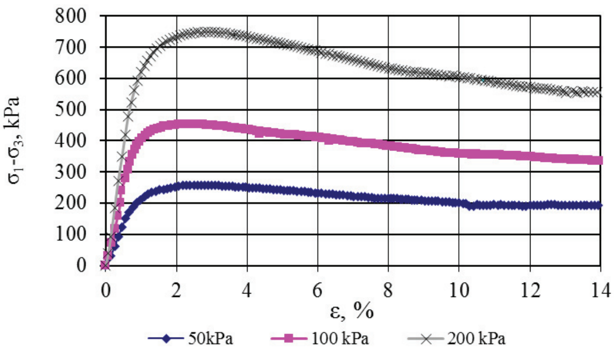


Fig. 2. Shear strength characteristics of sand in triaxial compression tests.

The evolution of the ratio of shear stress to the normal stress ($\tau/\sigma$) acting in the shear plane is shown in Fig. 3 for four laboratory tests carried out. It can be seen that the stress $\tau/\sigma$ max ratio is similar about 0,85 for three cases (100 kPa, 150 kPa, 200 kPa) and 0,73 for 50 kPa. The min ratio of $\tau/\sigma$ ranges from 0,65 to 0,7 for all loading cases (Fig. 3).

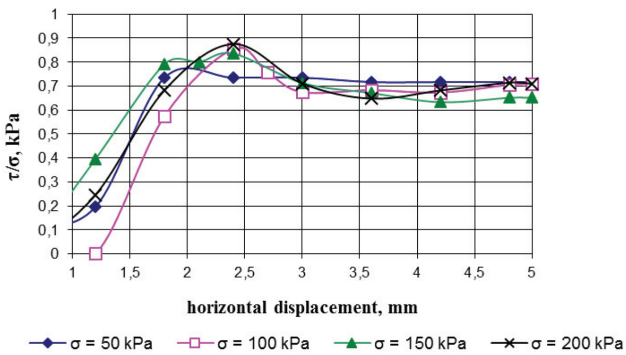


Fig. 3. Shear strength characteristics of sand in direct shear tests.

In dense sand there is a considerable degree of interlocking between particles. Before shear failure can take place, this interlocking must be overcome in addition to the frictional resistance at the points of contact. In general, the degree of interlocking is greatest in the case of very dense, well-graded sands consisting of angular particles [8]. During shearing of dense sand in direct shear test the macroscopic shear plane is horizontal but sliding between individual particles takes place on numerous microscopic planes inclined at various angles above the horizontal, as the particles move up and over their neighbours. The loading plate of the apparatus is forced upwards thus: work being done against the normal stress [9–11]. Correlation between the friction angle and the grain size distribution studies represented in reference [12].

The mean values of the soil shear strength parameters (Table 1) were calculated by means of methods provided in design regulations (the least squares method). The mean values of peak internal friction angle in both laboratory cases are different. The angle of internal friction related to peak stress from triaxial test is 2,36° less than obtained from direct shear test. The other researchers got comparable distinction [13]. The obtained mean value of the residual internal friction angle is lower by 2,95°.

Table 1. Mean values of soil shear strength parameters.

| Test type | Peak values | | Residual values | |
|---|---|---|---|---|
| | $\varphi_f$, ° | $c_f$, kPa | $\varphi_r$, ° | $c_r$, kPa |
| Direct shear test | 40,06 | 0 | 33,66 | 0 |
| Triaxial test | 37,70 | 0 | 30,71 | 0 |

## 3. Modeling of tests using three-dimensional finite element software

In order to evaluate the stress-strain state, the direct shear and triaxial tests were simulated with PLAXIS 3D software. Mohr-Coulomb model was used for evaluation of soil behavior. The model involves strength parameters - cohesion *c*, angle of internal friction $\varphi$, dilatancy angle $\psi$ and parameters of deformability - Young's modulus *E*, Poisson ratio $\nu$. The behavior of soil was modeled using values of soil strength parameters from laboratory tests data.

More than fifty years ago well-known researchers Terzaghi & Peck [14] highlighted disadvantages of conventional direct shear test. These include the effect of progressive shear failure initiated from edge of sample. This assumption was confirmed by the numerical tests. The mobilized shear strength distribution is shown in Fig. 4. Uneven distribution of shear stress may be identified as one of source of inaccuracy determining internal friction angle. Mobilized shear strength in plane are different. Shear strength near the sample edge is equal to 80–100 kPa, while in the middle only 20–40kPa.

a b

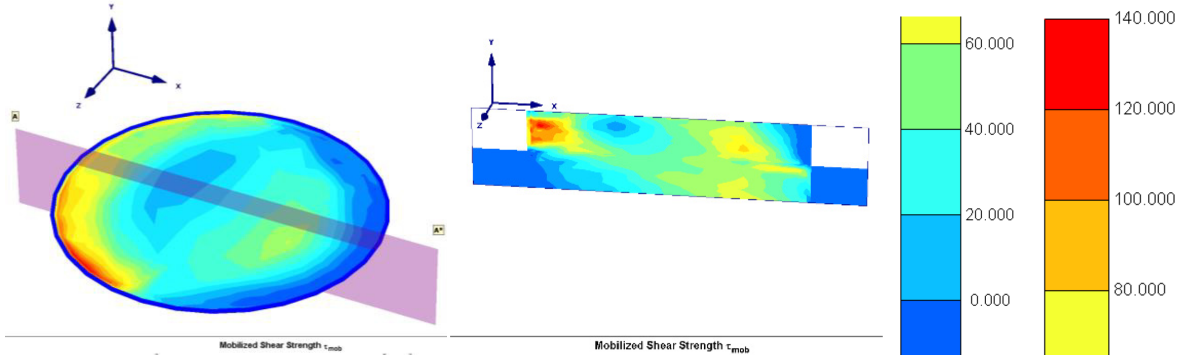


Fig. 4. Mobilized shear strength distribution (kPa) in: (a) shearing plane; (b) in cross section A-A.

Soil displacements over the shear plane distribution is irregular. As can be seen in Fig. 5 shearing plane is not smooth, likewise rough shearing plane obtained from laboratory tests.

a b

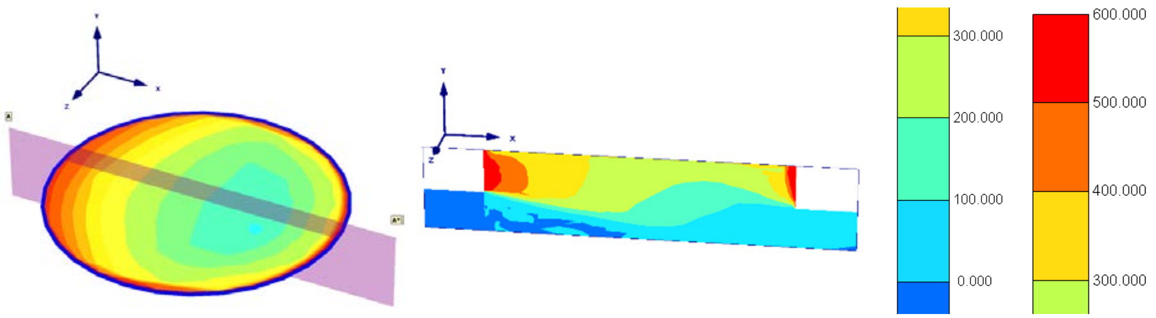

Fig. 5. Phase displacements $u_x$ ($10^{-3}$ m) in: (a) shearing plane; (b) in cross section A-A.

Normal vertical stresses are distributed not uniform too. It is clearly visible influence of friction between soil and device walls. Already after an initial compression phase of 100 kPa, walls influence is obtained (Fig. 6). Near the walls vertical stresses is smaller, acts only 60 kPa, while in the middle acts 100 kPa.

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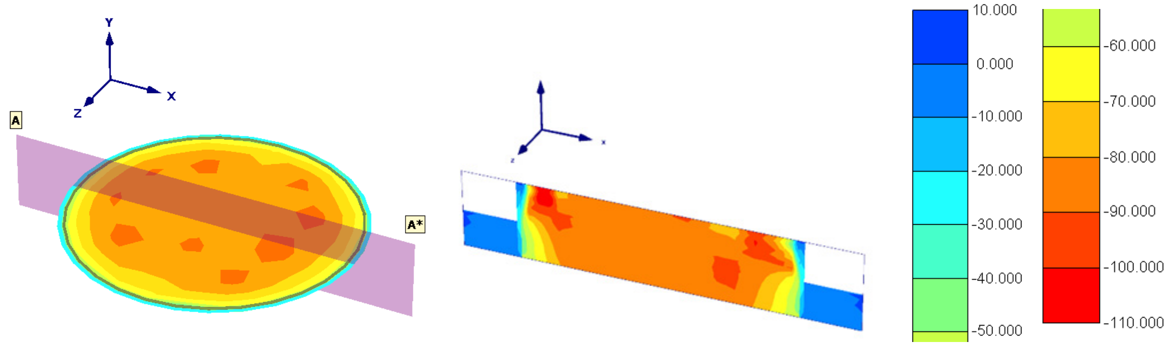


Fig. 6. Distribution of vertical stresses $\sigma_y$ (kPa) after an initial compression phase in: (a) shearing plane; (b) in cross section A-A.

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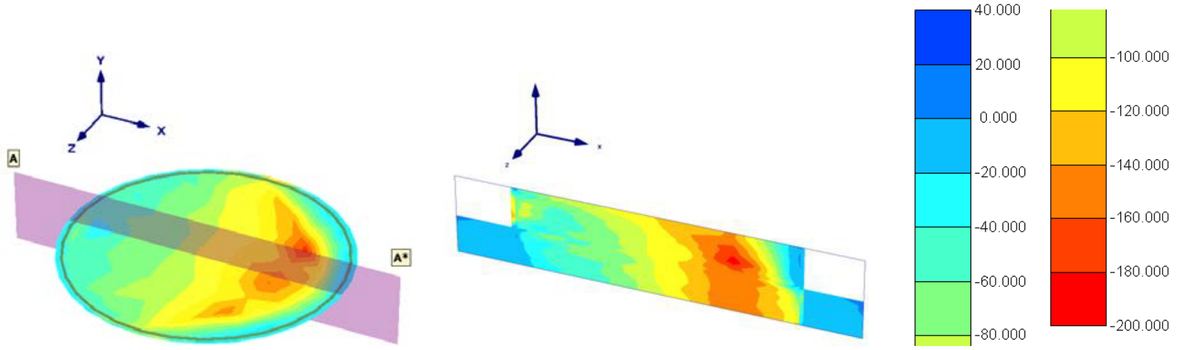


Fig. 7. Distribution of vertical stresses $\sigma_y$ (kPa) at failure phase in: (a) shearing plane; (b) in cross section A-A.

In failure phase of the vertical stress distribution is much more unequal (Fig.7). Vertical stresses varied from 60 kPa at the edge, 120 kPa at middle and 160 kPa near another edge of sample.

Numerical simulation of triaxial test revealed that distribution of stresses is completely different. Distribution of stresses is more uniform. Horizontal stresses distribution in confining stage and in failure stage is given in Fig. 8. Confining pressure of 100 kPa was applied. Influence of sample support on top and bottom can be seen very clearly. Confining pressure in the initial phase near the top and bottom of sample is only 65 kPa, meanwhile, in the failure phase significantly higher 170 kPa. In Fig. 9 can be seen vertical stress distribution during failure stage.

a b

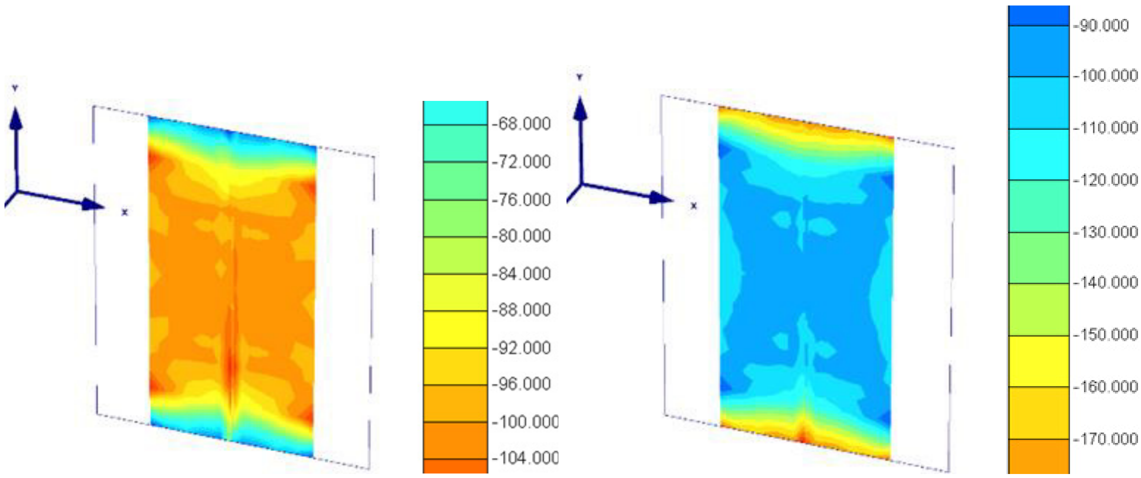


Fig. 8. Distribution of horizontal stresses $\sigma_x$(kPa) during confining stage (a) and failure stage (b).

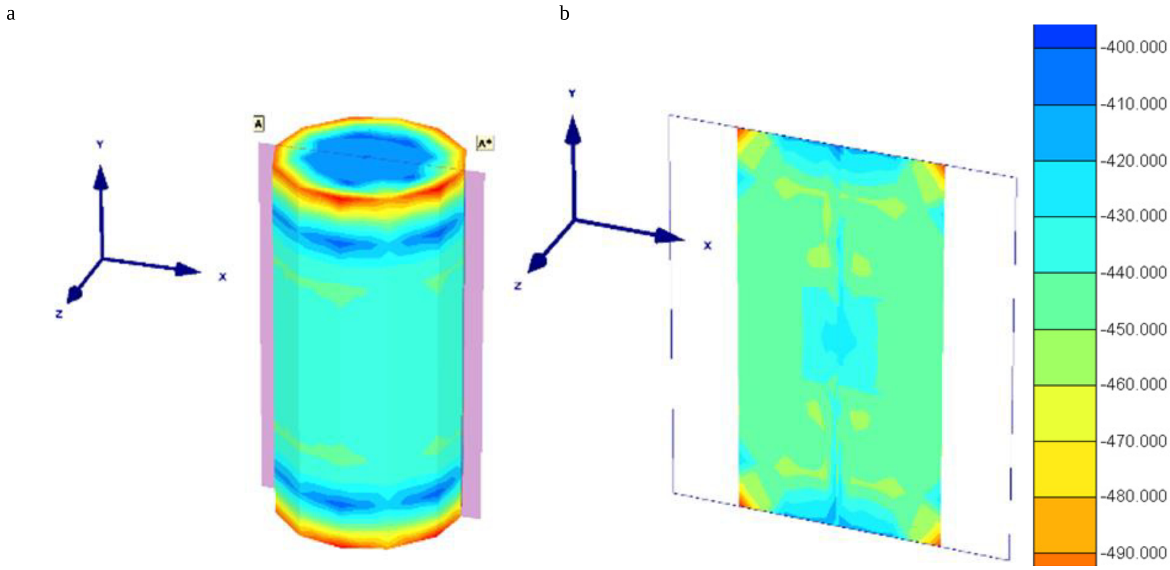


Fig. 9. Distribution of vertical stresses $\sigma_y$ (kPa) during failure: (a) whole specimen (b) cross section A-A.

Triaxial compression test simulation using Finite Element software showed that cap on specimen top and specimen base has influence on stress distribution. Vertical stresses in failure phase differences is small near the edge, meanwhile horizontal stresses variety is higher. At the top and bottom of sample is obtained shear stresses. Shear stress acting beneath cap (Fig. 10). During calculations of the strength parameter this phenomena is not evaluated. If it is assumed that on horizontal plane acts principal normal stress, shear stress on this plane must be accept equal to zero. Meanwhile, under top cap is acting up to 90 kPa shear stresses.

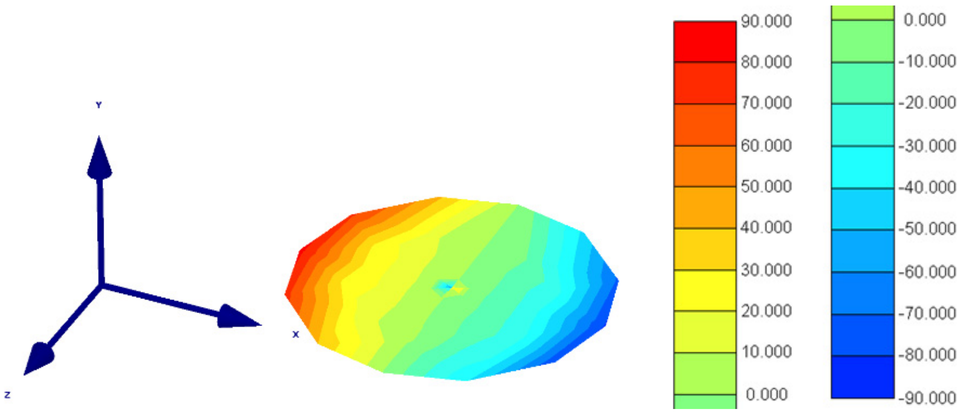


Fig. 10. Distribution of shear stress $\tau_{xy}$ during beneath cap at failure stage.

## 4. Conclusions

1. The obtained sand shear strength parameters from the results of the direct shear and triaxial laboratory tests are different. The peak angle of internal friction from triaxial test is 2,36° less than obtained from direct shear test, whereas the residual angle of internal friction differs by 2,95°.

2. The differences of the strength parameters values are caused due different stress-strain state, which is formed in samples during test.

3. In the direct shear device shear plane is not smooth. Also stresses in shear plane both normal and shear is allocated unevenly. Vertical stresses on shearing plane vary by more than three times, shear stresses more than two.

4. In sample stress is distributed uniformly during triaxial compression test. In top and bottom of the sample are affected not only principal normal stress, but also the shear stress. However, when calculating the shear strength parameters horizontal shear stresses are not considered.

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